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Extension of an agent-based simulation for the optimized allocation of freight requests to differently structured supply chains

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Abstract

The paper deals with the extension of the logistics simulation within an agent-based simulation framework to be able to consider the delivery across several supply chains. The logistics simulation is placed in the context of the underlying freight transportation simulation. The use of multiple possible logistics chains addresses a key limitation of previous studies. Logistics chains represent the various transportation options of a Logistic Service Provider (LSP) and are made up of resources such as depots, logistics hubs and carriers that the logistics service provider can commission. When implementing the new functionality, the existing flow of the simulation process must be considered. In particular, changes need to be made to the assignment of freight requests to logistics chains, the iterative optimization of this assignment and scheduling. Appropriate assignment methods and rescheduling strategies are developed and presented. These innovations reveal compatibility problems within the existing simulation framework. The functionality developed is presented in constructed scenarios, highlighting the advantages of using multiple logistics chains. In addition, the applicability is demonstrated in a comprehensive real scenario that includes the delivery of supermarkets.

Keywords: 2-echelon; logistics; agent-based; freight; MATSim

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1. Introduction and Motivation

Freight transport is important for the transition of the transport sector to carbon neutrality (European Commision, 2019). Due to the high degree of division of labor in the industry and the resulting widespread spatial distribution of production and storage facilities, there are numerous potential logistics chains (Holl and Mariotti, 2017). Logistic Service Providers (LSPs) are usually the players who decide which of these chains are used to transport goods (Cheng et al., 2022). This paper aims to contribute to the more efficient use of defined logistics chains in freight transport by examining different combinations of depots, hubs, and vehicles. The existing demand, in the form of freight requests, is to be optimally transported along a logistics chains, taking road charges into account. These are typical decisions

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when to use a one-echelon or a two-echelon logistic network, or even better, a combination of both. In the last few years, more and more research has been done regarding two-echelon Vehicle Routing Problems (VRPs), see e.g., Oliveira et al. (2022); Caggiani et al. (2020); Enthoven et al. (2020); Anderluh et al. (2019); Bakach et al. (2021). Yu et al. (2022) investigates the hybrid version of one- and two-echelon deliveries using delivery robots.

Advances in information technology enable agent-based approaches to become state-of-the-art in the field of transportation modeling (Nguyen et al., 2021). Due to a lack of behavioral principles, models for freight transport were for a long time not able to reflect logistical decision reactions well (Nagel et al., 2017 –). The use and further development of the Multi-Agent Transport Simulation (MATSim) transport simulation software opens up new possibilities for analyzing the use of logistics chains. In this paper, we provide a further development of an agent-based logistic simulation implemented in the MATSim simulation framework. It was originally implemented by Matteis et al. (2019), having the LSP as deciding agent. The most recent enhancement of this framework comes from Martins-Turner and Nagel (2022), who investigate two-echelon logistics chains.

2. Methodology and Software

2.1. Methodology

For this study, the extensible multi-agent simulation framework MATSim is used. MATSim allows extensions; extensions that are part of `matsim-libs` are called contributions, such as the *freight* contrib for freight transport simulation (Horni et al., 2016; Zilske and Joubert, 2016). For the current study, we are improving and enhancing the *logistics* extension, which is still under development (see Matteis et al., 2019; Martins-Turner and Nagel, 2022). In this study, we brought the simulation process of this future *logistics* extension closer to the standard MATSim process, which is explained briefly in Section 2.2. As mentioned before, the LSP is the responsible agent, deciding which shipment is transported on which logistic chain. More precisely, the data model is as follows:

- Each LSP has one or more plans, where each plan is one solution to fulfil the freight requests.
- Each plan has one or more logistics chains. An example for a logistics chain is: “The good is picked up at its origin, transported to hub A, from there to hub B, and from there to its destination.”

Martins-Turner and Nagel (2022) had only one unmodifiable logistics chain per plan of the LSP: Either doing a direct delivery *or* a two-echelon delivery for all shipments. The LSP was limited to the decision which of its plans it will execute. In the current work, we are using plans with more than one logistics chain. So it is also important to assign the different shipments on the different chains inside a plan. This happens once at the beginning as *initial assignment*. Later, in the replanning phase during the iterations, the LSP-plans can get modified. Therefore, different *replanning strategies* are developed. An (innovative) replanning strategy first copies the plan, and then modifies it, in this case by moving a shipment from one chain to another one. Plans are scored; plans with a larger score have a larger probability to survive and to be the basis for another innovative replanning step. First, we have tested and demonstrated the functionality of the different strategies in a simple simulation experiment (see Section 3). Afterward, it is applied to an existing case study (see Section 4).

2.2. Software

Basics of MATSim. MATSim is a Java-based, extensible multi-agent simulation that focuses on individual agents' daily courses (Horni et al., 2016). Agents compete, making decisions on routes, transportation means, activity scheduling, and destinations. Simulations run for a fixed number of iterations depicted in Figure 1, starting with the original demand derived from agents' activity sequences, described by the agents' plans (Horni et al., 2016).

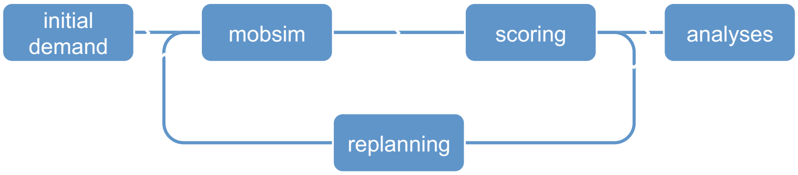


Fig. 1: The MATSim-loop (Source: Horni et al. (2016))

From a limited number of (initial) plans, the agents select a plan, which is then executed on the network. This is where congestion effects come into play. Each plan receives a score, whereby activities are valued positively, whereas trips are valued negatively. During the iterations, replanning allows the agents to modify their plans. The iterative process terminates when plan scores stabilize (Horni et al., 2016).

Freight transport simulation in MATSim. Carriers, with depots and vehicle fleets with certain capacities and costs, are responsible for shipping freight requests. Freight requests contain information on type, quantity, origin, destination, and time windows (Zilske and Joubert, 2016). As with passenger agents, the carrier agents' decisions influence their plans, comprised of freight-related activities, such as loading or unloading shipments. The open-source algorithm jsprit optimizes route planning in MATSim based on the available vehicles, aiming to minimize transport costs using a specific scoring system (Zilske and Joubert, 2016; Zilske et al., 2012). This solution is then simulated on the network where again, congestion effects cause additional costs for the carriers (Schröder et al., 2012).

Logistics simulation in MATSim. The logistics simulation retains the freight simulation functions while incorporating additional ones. The LSP takes on a superior role, making decisions on transport organization, while carriers still handle the tour and route planning. The LSP has resources in the form of hubs and carriers, which it can contract to transport the freight requests. This hierarchical structure offers flexibility, allowing LSPs and carriers to be treated as a single unit (Schröder et al., 2012). The resources are the elements of a logistics chain and thus represent a possible transportation route from the initial depot to the recipients.

This study extends the simulation to include the possibility of equipping an LSP with several of these logistics chains in the same plan. As a result, in the same plan, some shipments can be delivered directly, and others indirectly via hubs. Plan scores represent costs from resource use, encompassing carrier costs and fixed hub costs. Congestion effects influence carrier costs, impacting the LSPs decisions on logistics chain utilization. The LSP strives to optimize plans by reducing costs.

Replanning strategies for LSP-plans. The existence of multiple logistics chains allows for iterative optimization by redistributing shipments between the logistic chains of a plan. A central aspect of the current work is to develop suitable replanning strategies in the context of freight transportation. Three different strategies were developed for the approach of redistributing one shipment per iteration. The *RandomShiftingStrategy* redistributes one shipment randomly between logistic chains. The *RebalancingStrategy* shifts the first shipment of the most utilized chain to the least utilized chain. The *ProximityStrategy* moves shipments based on their destination. For this purpose, a random shipment is shifted to the logistics chain with the closest resource.

3. Simple Simulation Experiments

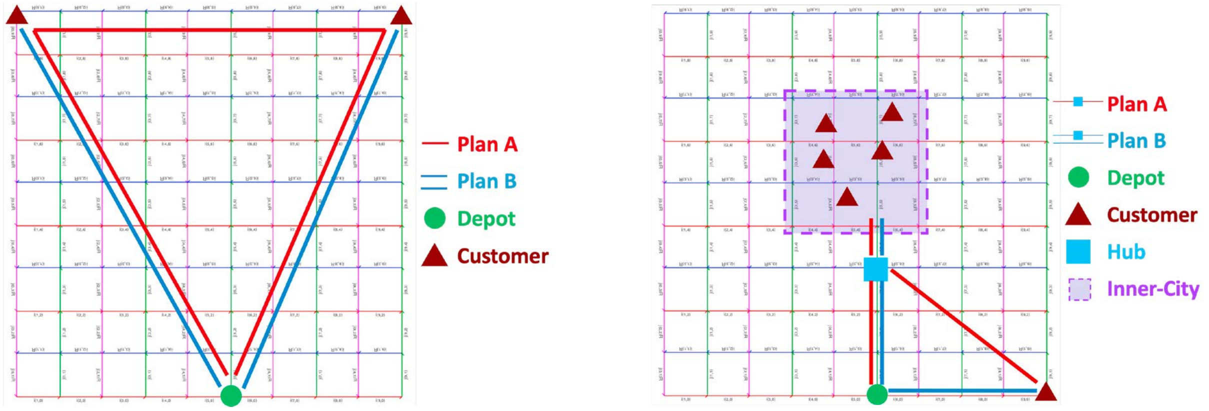
3.1. Setup

Example scenarios in a network with nine by nine single-directional links are used to illustrate the new functionality of several logistics chains in the same plan. Setup I (see Figure 2a) has one depot and two customers. Two LSP-plans are available. Both plans consist of one-echelon chains only. Figure 2b shows the demonstration setup II, which also includes two-echelon logistic chains. In all cases, 10 shipments are requested for delivery. The size of each shipment depends on the case and is set either to one or five.

The **network** is the same in both setups, with links of one kilometer length each and a maximum speed of 30 km/h, resulting in two minutes travel time per link.

Two different **vehicle types** are used. The small vehicle has a capacity of five, whereas the large vehicle can transport 50 units. The fixed and distance-dependent costs of a large vehicle are significantly higher (150 €, 0.01 €/m) than those of a small vehicle (5 €, 0.001 €/m). The time-dependent costs (0.01 €/s) do not differ, as it is assumed that these are personnel costs and are independent of the type of vehicle. In the tour planning, an unlimited number of each of these vehicles may be used.

In total, three different studies are run using the two different setups. For the first two studies, *no* replanning strategies are used. Over two iterations, both plans are executed once and in the final iteration the better scored plan is selected. The third study uses innovative replanning strategies over multiple iterations.



(a) Setup I: only one-echelon logistic chains are available: Plan A: One chain transporting all requests. Plan B: Two chains, on which the different requests can be split up by the LSP.

(b) Setup II: Mix of one- and two-echelon logistic chains per plan. Plan A: one two-echelon chain using the hub. Plan B: Two chains, one using the hub and one for direct delivery.

Fig. 2: Setup definition for the different studies. The optimal situation for our cases is shown: The requests are sorted onto the different chains depending on their customer's location (destination).

Case 1: Multiple-One-Echelon-Chains without *Replanning – Setup I, see Figure 2a.* Plan A (red) has one single direct delivery logistics chain with large vehicles, while Plan B (blue) has two direct delivery logistics chains with small vehicles, each. Each customer receives fives shipments of size one (subcase 1a) or five (subcase 1b). For plan B, the shipments are deliberately distributed separately to the logistics chains according to destination: The first chain gets all shipments to the left corner, and the second chain all shipments to the right corner.

Case 2: Multiple-Mixed-Echelon-Chains without *Replanning – Setup II, see Figure 2b.* Again, there are two plans: Plan A has a two-echelon logistics chain with large vehicles on the main run and small vehicles on the distribution run. The hub has a fixed cost of €100 per day. Plan B has additionally a single-echelon logistics chain with small vehicles. All ten shipments are of size one. Five shipments go to the customer in the lower-right corner. The other five shipments go to randomly distributed locations in the toll zone. In Plan A, all shipments are delivered via the hub. In Plan B, all shipments to the toll zone are on the two-echelon chain, and all shipments to the lower-right corner on the (direct) one-echelon chain. A prohibitively high cordon toll (€1000) prevents large vehicles from entering the inner-city zone.

Case 3: Multiple-One-Echelon-Chains with *Replanning – Setup I, see Figure 2a.* The structure is similar to the case 1a. But now, we only consider Plan B. The shipments are initially assigned randomly to the two logistics chains. For each of the different replanning strategies, we run over 200 iterations. In each iteration, either only a plan selection or the innovative replanning strategy is executed with equal probability. The goal is to see which of the replanning strategies leads to the optimal distribution, having all shipments to one location on one chain and all shipments to the other location on the other chain.

3.2. Results

Case 1: Multiple-One-Echelon-Chains without *Replanning.* With the shipment size of one (subcase 1a), Plan B is the better option because the total demand of ten can be transported by two small vehicles. Plan A with the large vehicle is much pricier, because of the higher cost rates.

With an increased shipment size of five (subcase 1b), Plan A is cheaper. The large vehicle is now fully utilized with a total demand of 50. Only the longer unloading times increase the time-dependent costs. Looking at Plan B, every small vehicle is fully loaded with one shipment already. Ten tours are therefore necessary to deliver all shipments, which is a significant disadvantage, especially when it comes to time-related costs. Table 1 gives more information.

Case 2: Multiple-Mixed-Echelon-Chains without *Replanning.* For Plan A there is one tour for the main run, and two tours for the distribution run. For Plan B, there is one tour for each run of the two-echelon-chains, as well as for the one-echelon chain. As can be seen in table 2, the fixed costs for the required vehicles and hubs are identical for both

Table 1: Results for case 1, using setup I: Plan A has one logistic chain and plan B has two logistic chains (see Figure 2a.)

shipment size	1				5			
plan	A		B		A		B	
vehicles	1 large	€150	2 small	€10	1 large	€150	10 small	€50
distance	36 km	€360	56 km	€56	36 km	€360	280 km	€280
time	82 min	€49.20	122 min	€73.23	122 min	€73.20	613 min	€367.57
total cost	-	€559.20	-	€139.23	-	€583.20	-	€697.57

Table 2: Results for case 2, using setup II: Resulting costs for plan A (red) and plan B (blue).

plan	A		B	
vehicles	1 large + 2 small	150+2*5 = €160	1 large + 2 small	150+2*5 = €160
distance	64 km	€136	40 km	€112
time	148 min	€88.83	95 min	€57.03
hub	-	€100	-	€100
total cost	-	€484.83	-	€429.03

plans. Due to the proximity to the depot, there is a saving in terms of distance and time-dependent costs if the five shipments are delivered directly to the lower-right corner.

Case 3: Multiple-One-Echelon-Chains with *Replanning.* When using the Random-Shifting-Strategy, the optimal allocation with the cost of €139.23 is achieved after 18 iterations. The Rebalancing-Strategy could not achieve the optimal distribution even after 200 iterations. The Proximity-Strategy does not cause any changes in this scenario because both chains use the same depot.

Case 3 also demonstrates that some aspects of the planning problem can be addressed at different levels. In the solution above, the grouping of the shipments to the two destinations is achieved by the assignment to the two chains. One could as well use only one chain, and then have the tour planning algorithm find the solution of having one tour with all shipments to the right and one tour all shipments to the left.

4. Application in a case study: Supply of supermarkets in Berlin

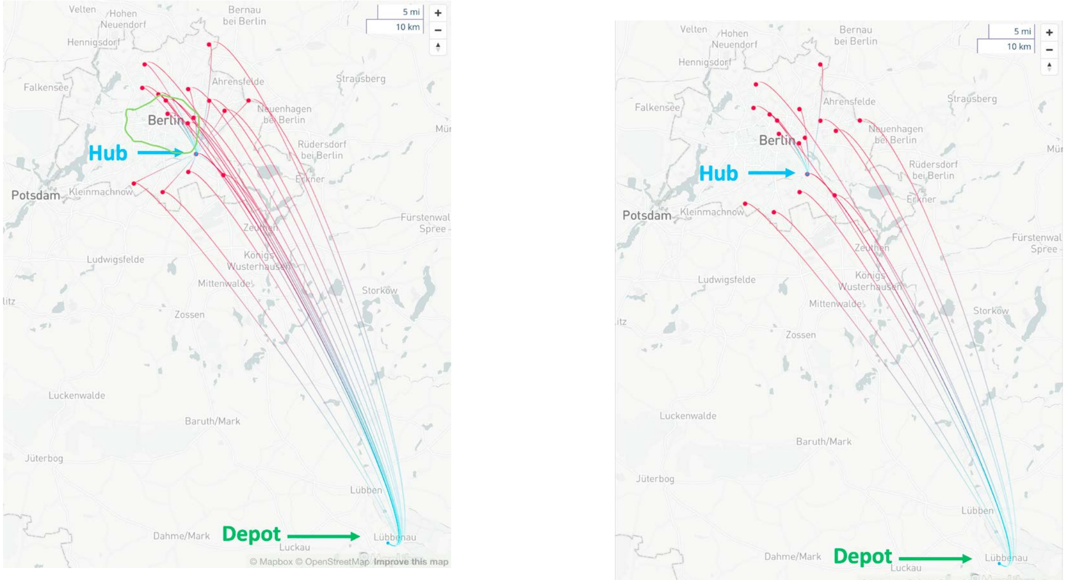
The newly implemented approach is now applied to an existing case study: The supply of grocery stores in Berlin. The original data for this study come from Schröder and Liedtke (2014) and were updated in more recent studies, e.g., by Martins-Turner and Nagel (2019); Martins-Turner et al. (2020). For the current study, we have selected only one carrier from this data set: Delivery of dry goods for Kaufland. The depot's location relatively far away from the stores is a useful use-case for investigating the application of a two-echelon delivery network.

Setup. The road network is taken from the Open Berlin scenario (Ziemke et al., 2019). In addition, a toll zone corresponding to the existing environmental zone is implemented. The cordon toll is set to a prohibitive value €1,000 for entering the zone with an Internal Combustion Engine Vehicle (ICEV). The hub is located nearby but outside the tolled zone with good connection to the freeway. The fixed daily costs of using the hub are set to €100. Figure 3a shows the location of the hub and depot, and from both the connections to the supermarkets.

We transferred the requests from this carrier to an LSP, including all requests. These are 17 shipments getting delivered from the depot to 16 stores. Five stores are within the toll zone and eleven outside. Each shipment's size is between 14 and 32 units.

The initial LSP-plan is set up with *two* logistics chains: a single-echelon chain with ICEV for the direct delivery from the depot to the supermarkets and a two-echelon chain with ICEV on the main run, the depot, and Battery Electric Vehicle (BEV) on the distribution run.

We are using two vehicle types from Martins-Turner et al. (2020). Both, ICEV and BEV, have the same (loading) capacity of 33 units. The time-dependent costs are the same as well: 20.12 €/h. Both types differ in fixed costs, which are €126.58 (ICEV) and €183.93 (BEV) per day and vehicle, as well as in the distance-dependent costs: 0.69 €/m for the ICEV and 0.78 €/m for the BEV. The shipments are initially assigned with different strategies (detailed below) to



(a) Scenario definition, with the location of the depot (origin), the hub, the different supermarkets (destinations), and the toll zone (green). Shown are the possible (generic) logistic chains.

(b) The resulting tours after the iterative simulation.

Fig. 3: Application of the improved simulation framework to a use case from Schröder and Liedtke (2014): The supply of supermarkets of a selected retail company in Berlin.

Table 3: Resulting costs and number of iterations needed to find the best plan, depending on different initial distributions of shipments to the chains.

Initial distribution of shipments	lowest costs	Iterations
all shipments on two-echelon chain	€6,619	183
randomly distributed on both chains	€6,631	58
both chains have half of the shipments each (even)	€7,089	77

either chain. We ran 200 iterations, with the *random shifting* replanning strategy. Afterward, we look at which iteration the best result (= highest score = lowest cost) is reached.

To assess the results of our new approach, we additionally simulate the two corner cases separately: i) all requests are delivered directly (one-echelon chain), and ii) all requests are delivered via the hub (two-echelon chain).

Results. The direct delivery alone is affected by the high toll costs, so the costs amount to €14,247. When delivering exclusively via the hub, these costs are significantly lower, at €8,311. Independently of the initial distributions of shipments, all plans with *two* chains were better than the corner cases with only one-chain plans. Table 3 shows that the initial assignment of *all shipments to the two-echelon chain* (and no shipment to the direct chain), followed by the Random-Shifting-Strategy as explained earlier, results in the lowest total cost. The *random* distribution on both chains is very close by in terms of costs, but on the other hand the solution was found three times faster. The *even* distribution on both chains had, together with the chosen replanning strategy, a significantly higher cost, which is nevertheless still better than using only chain for all shipments.

Based on these results, it cannot be judged how efficient the Random-Shifting-Strategy is. The number of iterations required depends heavily on the initial distribution and the optimal distribution. Local optima can occur, which can delay or prevent finding an optimum.

Figure 3b visualizes for the best best-performing LSP-plan found (total cost of €6,619) whether a store is served directly from the depot or via the hub. Due to the high toll fees, all stores within the toll zone are served by the two-echelon chain. Stores outside this zone are served either by the (direct) one-echelon or the two-echelon chain. Due to the restrictive shipment structure and the limited capacity of the vehicles, there are 22 tours: Six tours on the single-echelon logistics chain (cost of €2,078). The two-echelon logistics chain has eight tours each on both echelons

Table 4: Resulting values for the different carriers used in the best-performing LSP-plan: two chains, with an initial distribution of all shipments to the hub-chain. The daily costs of €6,629 consists of €6,519 for the carriers and €100 for the hub.

logistic chain	One-Echelon-Chain		Two-Echelon-Chain					Sum
echelon	(direct)		depot → hub		hub	hub → customer		
vehicles	6 ICEV	€760	8 ICEV	€1,013	-	8 BEV	€1,471	€3,244
distance	1,170 km	€807	1380 km	€952	-	211 km	€165	€1,924
time	1,523 min	€511	1,443 min	€484	-	1062 min	€356	€1,351
hub	-	-	-	-	€100	-	-	€100
total cost	-	€2,078	-	€2,449	€100	€1,992	-	€6,619

(depot → hub and hub → customer). The costs for the carriers on both echelons sum up to €4,441. Including the cost for the hub (€100), the two-echelon chain costs €4,541. For more details for the carriers of this LSP-plan, please refer to Table 4.

5. Conclusion and Outlook

In this work, we have improved an agent-based transport simulation framework. The focus is on the simulation of goods transport across a logistic network. We brought the current implementation of the LSP agent closer to the simulation standard of the software used. The LSP as an agent has (various) plans how to transport the goods (shipments) along its transportation network. For this, each plan consists of at least one transport chain to establish transport options for shipments through resources such as depots, hubs, and carriers.

Key steps of the simulation process are: initially assigning freight requests to logistics chains, modifying this assignment iteratively, and the subsequent disposition. Given past studies' focus on single (only one logistic chain per plan) logistics chains, new assignment methods and replanning strategies were necessitated, revealing compatibility issues with the existing program structure. Previously, shipment plans could only represent a single logistic route. The introduction of iterations emphasized the need to prioritize plans during selection and removal, and penalties ensure non-delivery of shipments remains disadvantageous. Now we added the possibility to have different logistic chains within one plan. This allows the LSP to decide to, e.g., transport some shipments directly to the customer, while other shipments are transported through a hub-and-spoke network. This improvement also includes the development of different strategies for an initial assignment of the requests inside a plan to the different logistic chains, as well as replanning algorithms for the iterative development of the plans. A replanning strategy defines how the distribution of requests to the differed logistic chains is being modified.

We demonstrated the new functionality first in a small, artificial scenario. In a second step, we applied it to an existing case study: The delivery of goods to supermarkets in Berlin. We show that the new approach works in general. Nevertheless, further testing of the developed replanning strategies for different use-cases and exploring additional options for replanning strategies is needed. This also includes combining different strategies. The combination of different replanning strategies presents an unexplored avenue. Despite observations that moving a single request from one chain to another may not suffice to exit local optima, shifting freight requests between logistics chains is just one dimension of optimizing delivery. Notably, the LSP still lacks the ability to rearrange predefined logistics chains from existing resources.

For future scenarios, considering a reward system for fulfilled requests could shift the evolution focus from pure cost considerations. This could eliminate the need for prohibitively high penalties for undelivered requests, as the negative cost component would naturally incentivize delivery. Empowering the LSP to decide whether requests should be fulfilled adds a new layer of flexibility. Schröder et al. (2012) offer inspiring approaches for extending MATSim-based logistics simulations, emphasizing the integration of goods and passenger transport. They advocate for modeling intermodal transport chains with diverse transportation modes, a perspective not covered in this work. Additionally, logistical decisions regarding shipment sizes and delivery frequency need to move beyond rigid factors in simulations (Bean and Joubert, 2020, 2021), while the predetermined location choices of depots and hubs in the form of logistics chains hinder capturing significant scale effects in logistics. Moreover, the use of another internal logic for the VRP algorithm makes sense: Switching from *services* to *shipments*, which allows the use of one vehicle for several delivery tours (see e.g., Martins-Turner and Nagel, 2019).

The present study primarily examines logistics chains originating from a common depot. Future investigations could delve into more complex networks with multiple starting depots utilizing a shared hub. Under certain conditions, this approach could further underscore the advantages of multiple logistics chains by minimizing distances and distributing fixed hub costs across multiple transport chains.

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